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# **Impact of performing heavy-loaded barbell back squats to volitional failure on lower limb and lumbo-pelvis mechanics in skilled lifters.**

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1   **Title**

2   Impact of performing heavy-loaded barbell back squats to volitional exhaustion  
3   on lower limb and lumbo-pelvis mechanics in skilled lifters.

4

5   **Abstract**

6   A common practice in resistance training is to perform sets of exercises at, or  
7   close to failure, which can alter movement dynamics. This study examined ankle,  
8   knee, hip, and lumbo-pelvis dynamics during the barbell back squat under a  
9   moderate-heavy load (80% of 1 repetition maximum (1RM)) when performed to  
10   failure. Eleven resistance trained males performed three sets to volitional failure.  
11   Sagittal plane movement dynamics at the ankle, knee, hip, and lumbo-pelvis were  
12   examined; specifically, joint moments, joint angles, joint angular velocity, and  
13   joint power. The second repetition of the first set and the final repetition of the  
14   third set were compared. Results showed that while the joint movements slowed  
15   ( $p < 0.05$ ), the joint ranges-of-motion were not altered. There were significant  
16   changes in most mean joint moments ( $p < 0.05$ ), indicating altered joint loading.  
17   The knee moment decreased while the hip and lumbo-pelvis moments underwent  
18   compensatory increases. At the knee and hip, there were significant decreases ( $p <$   
19   0.05) in concentric power output ( $p < 0.05$ ). Whilst performing multiple sets to  
20   failure altered some joint kinetics, the comparable findings in joint range-of-  
21   motion suggests that technique was not altered. Therefore, skilled individuals  
22   appear to maintain technique when performing to failure.

23

24   **Keywords:** fatigue; squat; strength training; kinetics; kinematics.

## 25     **Introduction**

26     The barbell back squat is a compound exercise frequently used to elicit both  
27     strength and power gains in the lower body musculature. When strength gains or  
28     hypertrophy are desired, a program consisting of heavy loads (85-100% of one-  
29     repetition maximum (1RM)) coupled with a low number of repetitions is  
30     recommended (Smilios, Häkkinen, & Tokmakidis, 2010). Conversely, moderate  
31     loads (40-60% of 1RM) and a high number of repetitions are employed to  
32     optimise muscular endurance and/or power (Farris, Lichtwark, Brown, &  
33     Cresswell, 2016). Irrespective of training methods, several sets of exercises are  
34     completed close to, or to the point of failure, so as to induce sufficient metabolic  
35     and neuromuscular training stimuli (Raeder et al., 2016). While exhaustion is  
36     expected when exercising at the completion of such working sets, it can cause  
37     changes in movement dynamics and increase the risks of injuries (Vakos, Nitz,  
38     Threlkeld, Shapiro, & Horn, 1994; Webster, Austin, Feller, Clark, & McClelland,  
39     2015). Thus, it is important for practitioners to understand and identify any  
40     compensatory movement patterns when performing resistance exercises to  
41     improve potential injury risk detection, reduce injury incidences, and ensure  
42     programs are safely and effectively executed.

43             Several studies have reported that mechanical stress significantly alters  
44     movement patterns during squatting exercises (Hooper et al., 2014; Hooper et al.,  
45     2013; Longpré, Acker, & Maly, 2015; Pick & Becque, 2000; Smilios et al., 2010).  
46     However, the majority of these studies have examined squatting mechanics  
47     following fatigue-inducing protocols. For example, Longpré and colleagues  
48     (2015) reported reductions in knee joint loading and vastus lateralis (VL)  
49     electromyographic (EMG) activity during squatting exercises after seated knee

50 flexion and extension exercises. Similarly, Smilios and colleagues (2010)  
51 observed decreases in VL and vastus medialis (VM) EMG activity during the  
52 concentric phase, decreases in concentric external work rates (power), and  
53 decreases in concentric movement speeds during squatting exercises immediately  
54 after performing four sets of 20 repetitions of squats at 50% of 1 RM. While these  
55 findings collectively suggest that injury risks may increase during squatting  
56 exercise performed after mechanical stress-inducing protocols, work is needed to  
57 examine if these changes are also present during working sets.

58         The work of Hooper and colleagues (2014) is one of the few studies that  
59 examined how squatting mechanics change over the course of working sets. They  
60 examined changes during a pyramid scheme (ten repetitions down to one) against  
61 an external load. In the early working sets, they observed a reduction in knee  
62 flexion coupled with an increase in the degree of trunk flexion. Accordingly, the  
63 performance of multiple sets against an external load, with minimal rest in-  
64 between, appears to alter squat mechanics, which may have implications for  
65 training practice and injury risks (Escamilla, 2001; Potvin, McGill, & Norman,  
66 1991). While the work by Hooper and colleagues (2014) gives insight into  
67 changes that can occur when multiple sets are performed, the resistance exercises  
68 were performed at moderate loads (i.e., 75% of 1RM), which is not optimal for  
69 muscular strength development. A more appropriate protocol is to use a heavier  
70 load and perform sets of exercises close to, or to the point of failure (Raeder et al.,  
71 2016). To the authors' knowledge, no study has examined the mechanics of  
72 squatting exercises under a heavy external load typically used to optimise strength  
73 development.

74           While previous findings on the impact of mechanical stress on squatting  
75   dynamics are insightful (Hooper et al., 2014; Hooper et al., 2013; Longpré et al.,  
76   2015; Pick & Becque, 2000; Smilios et al., 2010), there are a number of limiting  
77   factors. For example, knee joint dynamics have been the primary focus of most  
78   previous studies (Longpré et al., 2015; Pick & Becque, 2000; Smilios et al.,  
79   2010), with limited emphasis on other major lower limb joints, such as the ankle  
80   and hip, and how these contribute to the external work rates. It is possible that  
81   compensatory changes may take place at other lower limb joints which may  
82   increase injury risk, particularly during sets performed to, or close, to failure. In  
83   addition, previous work has examined the impact of load on the lumbar  
84   kinematics and found that increasing load results in significant increases in  
85   hyperextension, which in turn increases the compressive stress in the lumbar  
86   region (Walsh, Quinlan, Stapleton, FitzPatrick, & McCormack, 2007). However,  
87   the impact that fatigue has on lumbar kinematics and subsequent loading has  
88   received little attention. Finally, very few studies have examined working sets,  
89   particularly those performed to failure, with a heavy external load. While  
90   squatting to failure under a heavy external load (i.e., 85% of 1RM) has been  
91   reported to alter lower limb dynamics (Pick & Becque, 2000), squatting  
92   mechanics were only examined following a single set. Understanding the  
93   dynamics of squatting exercises performed to, or in proximity to, failure under  
94   moderate-heavy loads across multiple sets is essential as it is common practice for  
95   muscular strength and hypertrophic development (Raeder et al., 2016). The  
96   purpose of this present study was to examine how performing multiple sets to  
97   volitional failure alters ankle, knee, hip, and lumbo-pelvis kinetics and kinematics  
98   under a moderate-heavy load (i.e. 80% 1RM). It was hypothesised that performing

99 to volitional failure with result in significant alterations to ankle, knee, hip, and  
100 lumbo-pelvis kinetics and kinematics due to compensatory changes.

## 101 **Materials and methods**

### 102 *Participants*

103 Eleven resistance-trained adult males (age =  $26.2 \pm 3.8$  yrs; mass =  $82.4 \pm 8.9$  kg;  
104 height =  $1.78 \pm 0.08$  m; 1RM =  $138 \pm 19$  kg) participated in this study. An  
105 inclusion criteria required participants to be uninjured and capable of squatting  
106 one and a half times their body weight for 1RM without the use of lifting aids (i.e.  
107 weight belt or knee sleeves). According to an a priori sample size calculation,  
108 eleven participants was sufficient to generate a statistical power of 80% with an  
109 alpha level at 0.05 based on previously collected data (Hooper et al., 2013;  
110 Longpré et al., 2015). Procedures undertaken in this study were approved by the  
111 Institutional Human Research Ethics Committee and in accordance with the  
112 Declaration of Helsinki. All participants were informed of the potential risks and  
113 gave written informed consent at the commencement of their involvement.

114

### 115 *Procedures*

116 A within-subject repeated measures design was used, consisting of two sessions  
117 on two different days. The first session was a familiarisation session and the  
118 second was a data collection session. Within both sessions, participants were not  
119 permitted to use any lifting aids (i.e. weight lifting shoes, weight belts etc.) and all  
120 wore standardised footwear for both sessions.

121 Within the familiarisation session, participants first undertook a self-  
122 selected warm up routine which was noted and standardised across both sessions.

123 Following the warm up, their 1RM was determined. Participants were instructed  
124 to squat as deep as possible whilst using their regular technique (i.e., bar  
125 positioning, stance width, foot rotation, and movement speed) to optimise  
126 ecological validity (Southwell, Petersen, Beach, & Graham, 2016). Participants  
127 had 15 minutes recovery following the 1RM test before they completed a single  
128 set of back squats using 80% of 1RM for as many repetitions as possible  
129 (AMRAP). The AMRAP test was terminated when a participant could no longer  
130 lift the load (concentric failure). The AMRAP test was undertaken during the  
131 familiarisation session to ensure participants became familiar with the stress prior  
132 to data collection.

133         Once participants were fully recovered ( $\geq 2$  days) from the familiarisation  
134 session, they completed the data collection session. Within this session  
135 participants performed three AMRAP tests using 80% of their predetermined  
136 1RM with two minutes of rest given between each AMRAP test. Two minutes  
137 was chosen as this has been used previously when examining squatting and  
138 fatigue (Smilios et al., 2010).

139         In the data collection session, participants had retroreflective markers  
140 (Figure 1) positioned on anatomical landmarks of their lumbar and lower body  
141 (Besier, Sturnieks, Alderson, & Lloyd, 2003; Crewe, Campbell, Elliott, &  
142 Alderson, 2013a, 2013b; Vu, Walker, Ball, & Spratford, 2017). Markers were  
143 placed over the medial and lateral epicondyles, medial and lateral malleoli,  
144 calcaneus, heads of the first and fifth metatarsals, left and right anterior superior  
145 iliac spines, and left and right posterior superior iliac spines. Marker clusters  
146 consisting of three markers were affixed to the shank and thigh. Markers were  
147 also placed over the spinous processes of the first, third, and fifth lumbar



148 vertebrae and 5 cm lateral to the second and fourth lumbar vertebrae. These  
149 markers were used to define eight rigid segments being lumbar, pelvis, left and  
150 right thighs, left and right shanks, and left and right feet. Locations of the markers  
151 were tracked during the AMRAP tests using 10 infra-red Vicon MX-T40S  
152 cameras (Oxford Metrics, Oxford, UK). The cameras also tracked two markers  
153 positioned on either end of the barbell which allowed bar movement to be  
154 measured. Marker data were collected at 250 Hz. Two force plates (AMTI,  
155 Watertown, US) were used to collect the ground reaction force data acting on each  
156 foot (one foot per force plate). Force plate data were collected at 1000 Hz. All  
157 force plate and marker data were collected simultaneously within Vicon Nexus  
158 v2.6 (Oxford Metrics, Oxford, UK).

159

160 \*\*\*\*\*Figure 1 near here\*\*\*\*\*

161

### 162 *Data Processing and Analysis.*

163 Marker trajectory and analogue force plate data were post-processed within Vicon  
164 Nexus. All data were filtered using a fourth order low-pass Butterworth filter with  
165 a cut-off frequency of 12 Hz, defined following a residual analysis (Winter,  
166 2009). Joint kinetics were calculated using a standard inverse dynamics approach  
167 previously described in the literature (Besier et al., 2003; Crewe et al., 2013a,  
168 2013b).

169 To identify if changes in squat mechanics resulted from completing the  
170 three AMRAP sets, data from the second repetition of the first AMRAP test were  
171 compared with the last repetition of the third AMRAP test (i.e., final AMRAP

test). The second repetition of the first AMRAP test was treated as the baseline (i.e., non-exhausted state) as opposed to the first repetition to ensure stability (Legg, Glaister, Cleather, & Goodwin, 2017). The final complete repetition of the third AMRAP test was the repetition prior to the subject failing to lift the load, which was indicative of a working set, performed to failure.

Sagittal plane dynamics at the ankle, knee, hip, and lumbo-pelvis (defined as a segment between L1 and L5 relative to the pelvis) were examined. Specifically, joint moments, joint angles, joint angular velocity, and joint power were examined. Both moments and power were included as previous work has found that different compensations in these measures can occur at different joints (Farris et al., 2016; Flanagan & Salem, 2008). All joint moment and power data were normalised for system load (Legg et al., 2017). Discrete data points were derived from the time-series data of each leg and averaged to allow comparison between the movement in the second repetition of the first AMRAP and last repetition of the third AMRAP. The average moment during the examined repetitions at ankle, knee, hip, and lumbo-pelvis joints were determined to assess the joint load. The average moments at the aforementioned joints during the concentric phase were also determined to assess for changes in performance of the movement. The average power and joint angular velocity during the concentric phase at the ankle, knee, and hip were also examined to identify if work contributions changed with fatigue. Average power values were chosen over peak power as this is a better indicator of the amount of mechanical work done and the rate it was done at (Farris et al., 2016). To assess for range of motion changes, peak joint (sagittal plane) and bar displacements (all three planes) were determined. The average bar speed during the concentric phase was also examined

197 to identify if there was an overall change in the speed of the movement when  
198 fatigued.

### 199 *Statistical Analyses*

200 The measure of central tendency and dispersion of each dependent variable was  
201 reported as mean  $\pm$  standard deviation. Normality was assessed using the Shapiro-  
202 Wilk test with all data found to be normally distributed. Differences in the variables  
203 between the two time points were then examined using paired t-tests, with the alpha  
204 level set at 0.05. To determine the magnitude of differences between the two time  
205 points, effect sizes (ES; Cohen's *d*) were also computed and classified as trivial (0  
206 – 0.19), small (0.20 – 0.49), moderate (0.50 – 0.79), and large ( $\geq 0.80$ ) (Cohen,  
207 1988). All statistical analyses were carried out in SPSS v22 (IBM Corp., Armonk,  
208 USA).

### 209 **Results**

210 The average load lifted by the participants during the AMRAP tests was  $110 \pm 15$   
211 kg and the average number of repetitions completed was  $11 \pm 3$  in test one,  $7 \pm 2$   
212 in test two, and  $5 \pm 2$  in test three. Significant difference in mean joint moments  
213 were observed at the knee, hip, and lumbo-pelvis. At all three of the  
214 aforementioned joints, large effects were detected (Table 1; ES = 0.90 – 1.23).  
215 The hip and lumbo-pelvis saw significant increases of  $0.07 \text{ Nm.kg}^{-1}$  and  $0.14$   
216  $\text{Nm.kg}^{-1}$  respectively. The knee saw a significant decrease of  $0.06 \text{ Nm.kg}^{-1}$ .

217 Data for the concentric phase of the squat revealed there were a number of  
218 significant differences. Mean moments at the hip and lumbo-pelvis were altered  
219 (Table 1;  $p < 0.05$ ). A moderate effect was detected at the hip (ES = 0.73) where a  
220 significant increase of  $0.08 \text{ Nm.kg}^{-1}$  was observed. A moderate effect was also

221 detected at the lumbo-pelvis ( $ES = 0.72$ ) where a significant increase of  $0.16$   
222  $Nm.kg^{-1}$  was observed. For work rates, only power output at the knee and hip  
223 were altered (Table 1;  $p < 0.05$ ). A large effect ( $ES = 1.67$ ) was detected in the  
224 mean hip concentric power output where a significant decrease of  $0.15 \text{ Watts.kg}^{-1}$   
225 was observed. A large effect was also detected in the mean knee concentric power  
226 output where a significant decrease of  $0.34 \text{ Watts.kg}^{-1}$  was observed.

227 \*\*\*\*\*Table 1 near here\*\*\*\*\*

228 There were no significant differences in the range of motion at any joint  
229 (Table 1;  $p > 0.05$ ) or in the barbell range of motion (Table 2;  $p > 0.05$ ). While  
230 ranges of motion were not significantly altered, there were significant differences  
231 in joint angular velocities and in the speed of barbell movement during the  
232 concentric phase. Differences in mean joint angular velocity were observed at the  
233 hip, knee, and ankle (Table 1;  $p < 0.05$ ). Large effects were detected at all three  
234 joints ( $ES = 1.14 - 1.35$ ) where significant decreases of  $0.30 \text{ rad.s}^{-1}$ ,  $0.44 \text{ rad.s}^{-1}$ ,  
235 and  $0.14 \text{ rad.s}^{-1}$  were observed at the hip, knee, and ankle respectively. For the  
236 barbell movement, a large effect was detected in concentric speed ( $ES = 1.05$ )  
237 where a significant (Table 2;  $p < 0.05$ ) decrease of  $0.18 \text{ m.s}^{-1}$  was observed.

238 \*\*\*\*\*Table 2 near here\*\*\*\*\*

## 239 **Discussion**

240 The aim of this study was to examine the impact of performing heavy back squats  
241 (i.e., 80% of 1RM) to failure across multiple sets on squatting dynamics amongst  
242 experienced lifters. As has been the case with previous studies that have examined  
243 squatting during mechanical stress, performing a back squat exercise to failure

244 across multiple sets significantly altered the movement dynamics of a back squat  
245 exercise, possibly due to fatigue. In the current study, dynamics within the final  
246 repetition of the third AMRAP were significantly altered at the ankle, knee, hip,  
247 and lumbo-pelvis, with a reduction in barbell movement speed, suggesting that  
248 compensatory changes occurred. Overall, the findings suggest that some aspects  
249 of biomechanical movement patterns during a back squat are altered when  
250 undertaken to failure across multiple working sets.

251         The inability to maintain the barbell movement speed, was not surprising  
252 as there were also significant decreases in the angular velocity at the ankle, knee,  
253 and hip. Furthermore, others have also observed reductions in movement speed  
254 across multiple sets of back squats (Smilios et al., 2010). Given there were  
255 significant decreases in joint angular velocity it is not surprising decreases in joint  
256 power outputs were also observed as power is the product of the joint's angular  
257 velocity and moment (Winter, 2009). Smilios and colleagues (2010) have also  
258 observed significant changes to power output with fatigue. In the present study,  
259 reductions in power outputs at the knee and hip during the concentric phase were  
260 observed. At the knee this was also coupled with a small decrease in mean  
261 concentric moment which further explains the reduction in the knee power output.  
262 Interestingly however, at the hip the mean concentric moment increased with  
263 fatigue indicating that the decrease in joint angular velocity had a larger impact on  
264 the power output at the hip than the moment. The increase in hip moment suggests  
265 that the hip extensors supersede that of the knee extensors as individuals reach  
266 failure across multiple sets during the concentric phase. These biomechanical  
267 changes should be considered when prescribing back squat exercises to failure,  
268 particularly for individuals prone to hip injuries, or those returning from injuries.

269           For this cohort, there were significant differences in mean joint moments  
270   observed at the knee, hip, and lumbo-pelvis at the conclusion of the third  
271   AMRAP, indicating that joint loading was altered. A decrease in knee loading was  
272   detected which is in line with the work by Longpré and colleagues (2015) who  
273   observed reductions to knee moments during lunging and squatting following a  
274   fatiguing protocol. In this current study, the decrease in loading at the knee was  
275   coupled with an increase in loading at the hip. This suggests that as the  
276   participants fatigued, there may have been a compensatory change undertaken by  
277   the musculature surrounding the hip. Changes in muscle activation within these  
278   muscles have been observed in the work of others. In a previous study that  
279   examined changes during a single set to failure, Pick and Becque (2000) reported  
280   that the quadriceps muscle activation was at its greatest in the final repetitions  
281   prior to failure. Based on these findings, Pick and Becque (2000) highlighted the  
282   importance of prescribing repetition ranges that are at, or close to, to elicit  
283   sufficient levels of muscle activation for optimal strength adaptation. While this  
284   previous study highlights the importance of including sets performed to failure  
285   from a muscle adaptation perspective, it does not examine whether performing  
286   this type of activity in training could significantly alter an individual's movement  
287   dynamics and impact on injury risk. The results surrounding the mean moments in  
288   the current study gives insight into this.

289           Although joint loading was altered, there was no compromise in the range  
290   of motion of the lower limb joints. This finding is of particular importance in the  
291   lumbar region as any altered range of motion at this site may result in a loss of  
292   spinal stability, thereby increasing injury risk (Schoenfeld, 2010). While the range  
293   of motion in the lumbar region remained comparable, there was an increase in

294 lumbo-pelvis loading. This suggests that when approaching failure, greater  
295 stabilisation was required from the musculature in this region to maintain posture,  
296 which may have implications for injury risks. Thus, practitioners should  
297 encourage their athletes to rely on their task-intrinsic cues (e.g., kinaesthetic  
298 feedback) during back squats to failure, as visual feedback would be insufficient  
299 to detect kinetic alterations in the lumbar region with unaltered kinematics.

300         As noted above, the lower limb joint ranges of motion at the end of the  
301 third AMRAP were comparable with those observed at the start of the first  
302 AMRAP. These findings indicate that the participants were consistent with their  
303 technique, despite potential attenuation in muscular contractility, and  
304 compensatory movements were not induced which can put an individual at an  
305 increased injury risk and limit the effectiveness of the exercise (Escamilla, 2001).  
306 The non-significant change in joint range of motion conflicts with the findings of  
307 others who have examined the impact of fatigue within cohorts skilled in  
308 squatting exercises. Hooper and colleagues (2013) observed that fatigue caused a  
309 reduction in range of motion at the knee and hip however it should be noted that  
310 they examined body weight squats before and after an extreme fatiguing protocol  
311 whereas loaded squats were examined in the present study. In subsequent work by  
312 Hooper and colleagues (2014), they expanded their investigation to examine how  
313 the joint range of motion changed during the squatting component of a fatiguing  
314 protocol which consisted of back squats, deadlifts, and bench presses using 75%  
315 of 1RM. This work found there was less motion at the knee and a greater degree  
316 of trunk flexion at the start of the protocol and suggested this was a demonstration  
317 of self-preservation by their participants. This pattern of self-preservation was not  
318 observed in the present study, possibly due to the fact that only squats were

319 performed while the fatiguing protocol of the aforementioned study consisted of  
320 back squats, deadlifts, and bench presses. The technique changes observed by  
321 Hooper and colleagues (2014) are detrimental, due to the reduced knee flexion  
322 resulting in less muscle activity and the increased trunk flexion resulting in altered  
323 lumbar loading. The findings of this present study however, suggest that  
324 performing multiple sets to volitional failure does not appear to alter technique in  
325 the same way.

326       There are a number of limitations that should be considered within this  
327 study. A highly skilled cohort was examined, and thus findings may not be  
328 inferred to individuals with less experience in resistance training. While this can  
329 be seen as a limitation, the findings are highly applicable to practitioners who  
330 work with skilled individuals. In addition, the squatting mechanics were examined  
331 using a single load of 80% of 1RM. It would be beneficial to examine if dynamics  
332 are changed by incorporating varying loads. Future work could also consider  
333 examining mechanics throughout the entire working set to identify when  
334 technique alterations specifically occur.

### 335 **Conclusion**

336 The findings of this study indicate that, for experienced lifters, performing  
337 multiple sets to volitional failure results in some compensatory changes that could  
338 lead to increases in injury risk. Specifically, loading at the knee, hip, and lumbo-  
339 pelvis were altered. A reduction in the mean moment was observed at the knee  
340 while increases were observed at the hip and lumbo-pelvis. The increase at the hip  
341 may be a compensatory change due to the change at the knee while the increase at  
342 the lumbo-pelvis loading may lead to an increase the risk of injury and should be



343 considered when prescribing repetition ranges.

344 While the speed of the movement was reduced at the conclusion of the  
345 third set, there were no significant decreases in the joint range of motion which  
346 indicates that these individuals were not compromising squat depth. This is  
347 important from a strength development standpoint as a reduction in range of  
348 motion would result in less muscle activity (Escamilla, 2001). The reduction in  
349 movement speed was coupled with reductions in power output at both the knee  
350 and hip. This suggests that if practitioners are designating programs where power  
351 is of importance, then consideration should be given as to whether later working  
352 sets should be performed to volitional failure.

353 Future work should expand on this study to assess if the changes  
354 observed here are also observed when different loads are used and between  
355 differing skill levels.

356

#### 357 **Disclosure statement**

358 The authors report no conflict of interest.

359

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## TABLES

Table 1. Mean ( $\pm$ SD) of the magnitudes of the analysed joint variables in the second and final repetitions of the AMRAP test.

Variable	Second repetition				Final repetition			
	Joint				Joint			
	Hip	Knee	Ankle	Lumbo-pelvis	Hip	Knee	Ankle	Lumbo-pelvis
Mean moment (Nm.kg <sup>-1</sup> ) <sup>ABC</sup>	0.74 (0.09)	0.76 (0.12)	0.21 (0.10)	1.70 (0.14)	0.81 (0.12)	0.70 (0.11)	0.27 (0.10)	1.84 (0.15)
Mean concentric moment (Nm.kg <sup>-1</sup> ) <sup>DE</sup>	0.76 (0.12)	0.69 (0.13)	0.23 (0.14)	1.76 (0.22)	0.84 (0.14)	0.62 (0.15)	0.29 (0.13)	1.92 (0.18)
Mean concentric angular velocity (rad.s <sup>-1</sup> ) <sup>FGH</sup>	1.09 (0.08)	1.50 (0.25)	0.47 (0.09)	-	0.79 (0.24)	1.06 (0.30)	0.33 (0.12)	-
Mean concentric power (Watts. kg <sup>-1</sup> ) <sup>IJ</sup>	0.62 (0.10)	0.89 (0.20)	0.11 (0.07)	-	0.47 (0.13)	0.55 (0.15)	0.10 (0.05)	-
Peak angle (°)	107.34 (9.90)	124.36 (15.88)	37.2 (8.23)	18.60 (4.82)	110.03 (13.97)	127.59 (18.43)	38.50 (7.20)	18.98 (5.83)

<sup>A</sup> Significant increase in mean moment at the hip ( $p = 0.01$ ; ES = 1.08)

<sup>B</sup> Significant decrease in mean moment at the knee ( $p = 0.02$ ; ES = 0.90)

<sup>C</sup> Significant increase in mean moment at the lumbo-pelvis ( $p = 0.00$ ; ES = 1.23)

<sup>D</sup> Significant increase in mean concentric moment at the hip ( $p = 0.046$ ; ES = 0.73)

<sup>E</sup> Significant increase in mean concentric moment at the lumbo-pelvis ( $p = 0.049$ ; ES = 0.72)

<sup>F</sup> Significant decrease in mean concentric angular velocity at the hip ( $p = 0.00$ ; ES = 1.35)

<sup>G</sup> Significant decrease in mean concentric angular velocity at the knee ( $p = 0.00$ ; ES = 1.26)

<sup>H</sup> Significant decrease in mean concentric angular velocity at the ankle ( $p = 0.00$ ; ES = 1.14)

<sup>I</sup> Significant decrease in mean concentric power at the hip ( $p = 0.00$ ; ES = 1.67)

<sup>J</sup> Significant decrease in mean concentric power at the knee ( $p = 0.00$ ; ES = 1.50)

Table 2. Mean ( $\pm$ SD) of the magnitudes barbell displacement and velocity in the second and final repetitions of the AMRAP test.

	Second repetition	Final repetition
Vertical displacement (m)	0.60 (0.08)	0.57 (0.15)
Antero-posterior displacement (m)	0.06 (0.17)	0.08 (0.05)
Medio-lateral displacement (m)	0.02 (0.01)	0.03 (0.01)
Mean concentric velocity ( $\text{m}\cdot\text{s}^{-1}$ ) <sup>A</sup>	0.48 (0.06)	0.30 (0.13)

<sup>A</sup> Significant decrease in mean barbell velocity during the concentric phase ( $p = 0.00$ ;  $d = 1.50$ )

## **FIGURE LIST**

Figure 1. Retro-reflective marker set used to define the body as eight rigid segments being lumbar, pelvis, left and right thighs, left and right shanks, and left and right feet. Sagittal plane movement dynamics at the ankle, knee, hip, and lumbo-pelvis were derived from the three-dimensional marker data. Note: some additional markers there are not defined in the text are visible but were not used for any calculations.